Telerehabilitation: Controlling Haptic Virtual Environments through Handheld Interfaces

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ABSTRACT

This paper presents a telerehabilitation system for kinesthetic therapy (treatment of patients with arm motion coordination disorders). Patients can receive therapy while being immersed in a virtual environment (VE) with haptic feedback. Our system is based on a Haptic Workstation that provides force-feedback on the upper limbs. One of our main contributions is the use of a handheld device as the main interface for the therapist. The handheld allows for monitoring, adapting and designing exercises in real-time (dynamic VE). Visual contact with the patient is kept by means of a webcam.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Haptic I/O, Input devices and strategies*; J.3 [**Computer Applications**]: Life and Medical Sciences—*Health*

General Terms

Experimentation, Human Factors, Design

Keywords

telerehabilitation, haptic interfaces, handheld devices, kinesthetic therapy, virtual environments

1. INTRODUCTION

The work we present in this paper is based on the use of haptic interfaces and reconfigurable virtual environments as tools for telerehabilitation.

Our research focuses on implementing a telerehabilitation system for kinesthetic therapy for patients with motion coordination disorders of the upper limbs. The therapy is targeted to help patients who have lost precision/control of their arm-hand gestures. This disorder is frequently the consequence of a traumatism. The patients are unable to follow a given trajectory in space. They cannot control their movements and/or have lost the notion of space depth (spatial reasoning).

Figure 1: Telerehabilitation system, haptic virtual environment controlled through a handheld interface. Picture on the left shows the patient's view of the VE.

The therapy we have designed consists on having the patient follow different trajectories with her hands while immersed in a virtual environment with haptic feedback, see figure 1. Trajectories are represented as 3D pipes lying on a 2D plane in front of the patient. The idea is to keep the hands inside the pipe, without touching the borders. The patient can see her hands in the virtual environment and feel when she touches the virtual object. The therapist uses a handheld interface that allows for creating and modifying the pipes in real-time. While the patient stays in the hospital using our teleoperation system, the therapist can monitor and control the treatment at distance, from any location with Internet access.

This paper describes the architecture and discusses the potential benefits of the system we have designed. One of our main contributions is the use of a handheld device as interface for controlling the virtual therapy environment.

The handheld helps on monitoring the patients' performance as well. We show the feasibility of implementing dynamic and fully immersive environments with haptic feedback which can be remotely controlled/adapted through a handheld interface. The formal evaluation of this technology in the context of kinesthetic therapy is let as future work.

The rest of the article is organized as follows: next section overviews related work concerning the use of Virtual Reality and haptic interfaces for rehabilitation. We analyze the advances in the emergent area of telerehabilitation. After we present our contribution in detail: the design of a system architecture and a handheld interface for real-time configuration and monitoring of virtual environments with haptic feedback. We present a semantics-based representation of virtual environments which serves as foundation for the therapy virtual environment. Then we describe the application we have implemented in the contexts of kinesthetic therapy and telerehabilitation. The paper concludes with a discussion of results and our plans for future work.

2. RELATED WORK

Several studies have demonstrated the effectiveness of VR environments in the treatment of motor disorders. For instance, the work of Piron et. al. [18] shows the benefits of VR-based training on the rehabilitation of patients with ischemic strokes. Other examples of VR-based post-stroke rehabilitation are the works of Boian et. al. where the authors proposed a set of VR exercises for post-stroke hand [2] and ankle rehabilitation [1] . Nair et. al. [16] created a low-cost tool for diagnostic and rehabilitation of people with upper limb dysfunction due to muscular dystrophy and stroke. Camurri et. al. [4] presented a therapy environment for Parkinson's patients based on gesture analysis and recognition.

An artificial environment that resembles, but do not fully emulates the real world conveys a particular feeling of novelty. This can motivate the patient and keep her interest on the therapy. The work of Loureiro et. al. [14] shows how the patient's attention and motivation can be improved through the right combination of visuals and haptic technologies.

From the therapist's point of view, VR offers another added value: clinical assessment through detailed recording of patient's performance and behavior. For instance, the work of Goncharenko et. al. [7] emphasizes the use of "history units" - recordings of simulation parameters and patient's motions- in post-rehabilitation analysis of human performance. The recorded information is a valuable resource for improving and adapting the therapy and simulation models to better fit the personal needs of each patient.

More comprehensive reviews of the numerous benefits - and challenges- of using Virtual Reality and haptic technologies on rehabilitation can be found in the articles by Schultheis and Rizzo [21], Burdea [3], and Holden and Todorov [11].

Researchers agree upon the fact that one of the greatest advantages of VR and haptics is that they can be personalized for the particular requirements of each patient. These technologies offer great flexibility in terms of dynamic creation and edition of 3D environments and simulation models. An additional benefit is their recording and measuring capabilities. However, most of the systems implemented so far allow for a rather limited parameterization and are unable to modify the 3D environment in real-time.

The latter would be specially useful to create a more interactive experience and enhance the adaptation to each patient. If the therapist had a simple way to monitor and change the environment -including the haptic feedback-, then the patient's attention and motivation could be increased even more. For instance, the repetitive nature of therapy could be alleviated if the therapist were able to change the therapy exercises in real time, according to the progress achieved during the current session. The motivation and interest of the patient could be kept high by means of designing a more complex routine or simplifying the current one in real-time.

Another particularly interesting possibility concerns the concept of telerehabilitation. This has been studied by several researchers. Popescu et. al. [19] implemented a PC-based orthopedic rehabilitation system allowing for remote monitoring of patients. Piron et. al. [17] presented a VR system for motor telerehabilitation using visual feedback.

One of the main ideas behind the rehabilitation at distance is to give more comfort for the patient, avoiding displacements to the hospital and supporting independent living for individuals with disabilities [20]. Holden et. al. [10] presented a system for home-based telerehabilitation. Their application demonstrated to be an effective way for therapists to conduct treatment sessions. Increasing the action range of therapists, enabling them to reach more patients is another valuable benefit of telerehabilitation. The work of Lewis et. al. [13] shows the potential of internet technologies. The authors developed a web-based system for telerehabilitation monitoring.

Despite the advances in this research area, we believe that not enough emphasis has been put on the adaptability of the rehabilitation environment. The systems we cited above allow for monitoring, logging the patients performance and keeping a two-way communication between therapist and patient. But they do not allow for reconfiguring the virtual environment in real-time. Interaction possibilities for the therapist are rather limited, in the sense that she cannot modify the pre-defined therapy exercise during the treatment session. Currently, the monitoring interfaces are implemented in a PC. This constraints the therapist's mobility, forcing her to sit in front of the computer to follow the performance of the patient.

Our main contribution focuses on providing a compact mobile interface for monitoring, configuring and editing the rehabilitation environment in real-time. We believe that giving full control of the virtual environment to the therapist through a networked handheld interface can enhance patient-therapist communication and improve the effectiveness of telerehabilitation. Next section describes our system architecture.

3. SYSTEM ARCHITECTURE

Our architecture for telerehabilitation systems is based on the following requirements:

- using fully immersive environments with haptic feedback
- keeping close communication between therapist and patient
- giving the therapist full control over the virtual environment

3.1 Haptic Feedback

First we must define the specific type of virtual environment we want to use. We have chosen the full-immersion approach, a system where the user gets inside the virtual world by means of a Head Mounted Display. We believe this is an interesting alternative. Full immersion can enhance the patient's interest. This kind of systems isolate the user from the real world and allow for deeper concentration on the exercise.

We target physical rehabilitation, thus, we will use direct interaction techniques inside the virtual environment. This means the patient will see a representation of his hands or the specific limb under treatment.

In section 2 we pointed-out the importance of haptic feedback for an effective therapy. We will exploit the advantages of a Haptic Workstation^{TM} [12]. This device, conceived for virtual prototyping, provides two-handed force-feedback and is a versatile tool. Our architecture intends to evaluate it in the context of physical rehabilitation. Obviously, for the moment we restrict ourselves to upper-limb therapy. However, the concepts and the rest of the architecture are not hard-linked to the use of the Haptic Workstation and can take advantage of other haptic interfaces.

3.2 A "Window to the Real World"

As affirmed by Loureiro et. al. [14] attention and motivation are keys for recovery. We believe these can be achieved through an appealing therapy environment. However, special care should be put on the therapist-patient communication as well. Human contact is essential. The therapist plays not only the role of doctor and specialist but acts as coach or friend. In a telerehabilitation scenario, the audio-visual contact should be kept by means of teleconferencing technologies.

A webcam with microphone is a convenient solution to ”send” the therapist into the patient's place. In our full-immersion-based architecture we keep human contact by means of a ”window to the real world”, a virtual screen that displays live video of the therapist. This way, the patient immersed in a virtual environment is linked to the real world. The live image allows for demonstrating the therapy exercise and accompanying the patient through the first trials. This can be an effective way for correcting the patient's gestures and encouraging her to keep trying.

3.3 Remote Control of Virtual Environments

An on-line therapy system is not complete unless we close the communication loop. The therapist needs to monitor the patient's performance. Being able to adapt the therapy environment to the current needs of the patient is essential. Closing the communication loop with a second webcam located on the patient's side would not be enough. The therapist requires more detailed information such as performance statistics, clinical history, and a way to modify the environment.

Here is where we make our main contribution. The therapist requires control over the therapy environment in order to dynamically adapt the exercises to the current needs of the patient. For instance, the patient's mood could make her get bored faster than usual. She could find the routines harder than they actually are. The therapist could take the decision of modifying totally or partially the current exercise to better fit the patient's mental and physical conditions.

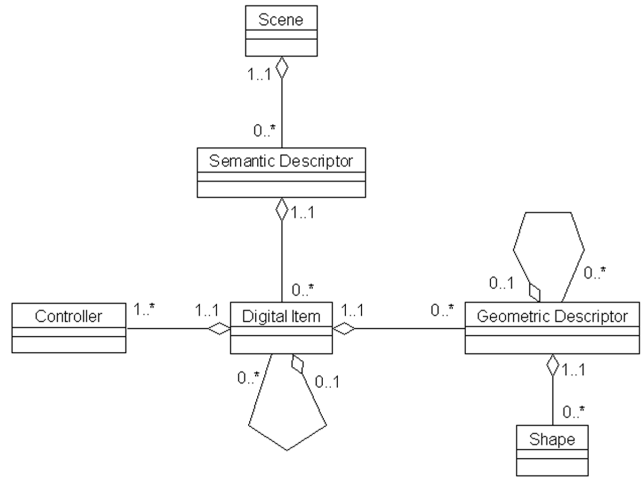

Figure 2: UML diagram of a generic semantic model for interactive virtual environments.

Such a detailed control of the therapy environment requires an easy-to-use, non-cumbersome interface. The interface should allow for keeping direct visual contact with the patient and freedom for gesturing with the arms. The therapist must be able to demonstrate the exercises and encourage the patient. Instead of placing the therapist in front of a PC with a webcam, we put the essential tools and information in the palm of her hand by means of a handheld device.

PDA or handheld devices have been successfully used to complement or even eliminate the need for PC-based interfaces to virtual environments, e.g. [8], [9], [6]. Tests have shown the feasibility of using a handheld to control and interact within a VR application. A handheld interface maximizes the user's freedom of motion without loosing neither control nor ease of use. Thus, we apply the concept of handhelds as interaction tools to VR in the context of telerehabilitation.

The central idea of our system architecture is giving to the therapist the possibility of monitoring and reconfiguring the therapy environment in real-time. We want our system to be as flexible as possible. The next section describes the way we have modeled the therapy environment by means of a generic representation of virtual environments.

4. DATA MODEL

Instead of implementing an ad-hoc application for a unique test case we have defined a flexible system architecture. The objective was to specify the infrastructure for developing a variety of applications involving multiple interaction terminals (haptic virtual environments, handheld/PC-based interfaces, etc.).

We designed a data model based on the semantics of virtual entities. We consider virtual objects not as 3D shapes but as items with a set of functionalities (semantics) which can be used in different contexts. Virtual entities should be rendered (visually and haptically) in different ways depending on the terminal (therapy VR environment, handheld interface, etc.).

In this case we need to render the virtual entities to be used in the therapy environment. This includes the virtual objects with which the patient interacts, as well as the virtual hands - the patient's interface. Such virtual objects must be editable by means of a mobile handheld device. At the same time, the patients performance must be monitored using the same mobile interface. For instance, the hands of the patient should be tracked and visualized both on the therapy environment and on the handheld.

Geometric and functional descriptions, as well as state variables of the virtual entities (current position, etc.) are maintained in a central data repository. The semantic data repository acts as a mediator/translator between the handheld interface and the complex haptic virtual environment.

Figure 2 shows an UML diagram of the main components of the semantics-based model that we have defined.

The **Scene** is the main container of the VE model; it has references to the digital items contained in the VE. A **Semantic Descriptor** provides human and machine readable information (XML documents) about a particular digital item or virtual entity. They are the entry points for the scene controller. They are used to choose the most appropriate geometry and interface to present. The semantic descriptor is the placeholder for any information describing how the digital item is to be used and how it is related to other items in the scene.

The **Geometric Descriptor** of a digital item specifies the type of Shape associated to the entity: a 3D mesh to be used in the therapy environment, or an articulated body composed of joints and segments to represent the patient's hands, etc. Hierarchical structures for skeleton-based animation -for the virtual hands- can be defined using geometric descriptors.

Virtual entities can be represented with different shapes depending on the context in which the are used. For instance, on a handheld interface the therapist does not require a 3D view but only a schematic representation of both the patient's hands and the interactive entities. Alternative geometric representations for each virtual entity can be defined by means of **Shape** descriptors, this idea is illustrated in figure 3.

Our model reflects also the relationships between the entities. The semantic descriptors characterize each object in the scene. They constitute a scene graph that can be used both for rendering and extracting underlying information about its contents. For instance, such information is used for collision detection and generation of force-feedback under the haptic VE. Digital items can contain other items or be related to each other in different ways.

A Digital item can be edited through the handheld interface or follow the motion of the user's hands. **Controllers** specify the interaction possibilities and expose the parameters controlling their behavior.

This semantic model provides us with an ensemble of design patterns to represent the information required for controlling and interacting within a virtual environment. The next section describes the application we have developed applying this model.

5. KINESTHETIC THERAPY

Using the system architecture outlined before, we implemented an application to be used in the context of rehabilitation. The target users are people with motor coordination

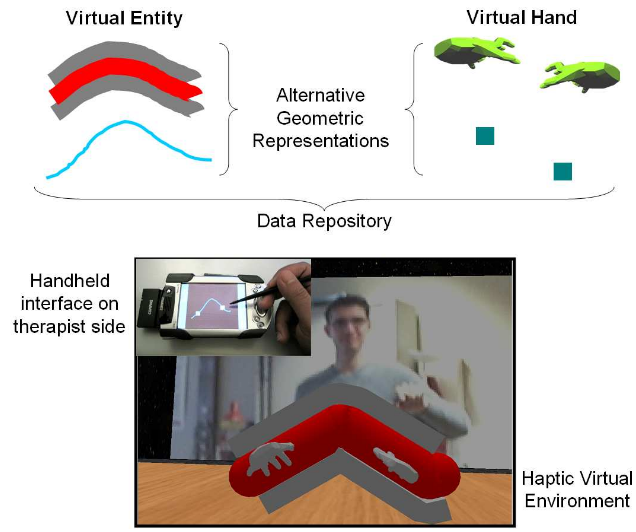

Figure 3: Virtual entities share semantic meaning and have context-dependent shape representations.

and/or spatial perception impairments. They are unable to perform precise gestures with their arms. For instance, reaching objects in space or tracing an imaginary circle in the air or some other geometric shape with their hands is a complex task for them.

The therapy we designed consists on following different trajectories with the hands while immersed in a virtual environment with haptic feedback. The patient can touch and feel trajectories build with 3D pipes by the therapist. The objective is to help patients on recovering motion coordination through frequent and varied exercises. The therapy is enhanced by means of a fully immersive virtual environment with haptic feedback provided by a Haptic Workstation ^{TM}.

The virtual environment contains 3D pipes that the patient has to reach and follow with the hand. The pipes lay on a 2D plane in front of the patient (constant depth). The haptic workstation provides force-feedback to simulate the borders of the pipe. The goal is to avoid touching the pipe while following the trajectory designed by the therapist. An inverse therapy can be foreseen: using the force-feedback to guide the patient's gestures. The "haptic assistance" could be gradually reduced according to the progress achieved.

To create the pipes, the therapist draws a line on the handheld's screen. The pipe's width can be modified at any time to ease the exercise or make it more challenging, according to the current performance of the patient. The exercise is monitored and edited by the therapist in real-time. The therapist can track the position of the patient's hands, represented as squares on the screen (see figure 4).

Patient's performance is logged automatically to get a detailed progress report. An XML file is generated for each session containing the following data:

- 3D pipes defined as an array of 2D points
- scalar values indicating the pipe's width
- position of the hands sampled at 25Hz

Each data element is time-stamped so that the session can be accurately reproduced from the XML log-file.

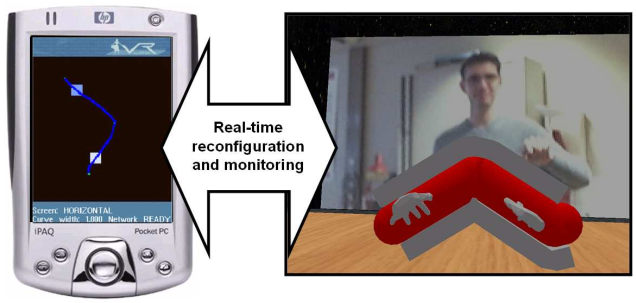

Figure 4: Handheld-based interface and immersive virtual environment, patient's performance (hands position) is monitored through the handheld.

At the end of the session the therapist has a record of the different pipes that were used and the way they were followed by the patient. This log file can be used to analyze patient's progress. The pipes drawn can be reused in subsequent sessions to compare the patient's performance.

The therapist keeps direct contact with the patient through a webcam. Live video is displayed in the therapy environment on a virtual screen. The virtual "window to the real world" gives to the patient the illusion that she is sitting just in front of the therapist.

5.1 Implementation Details

See figure 5 for a general view of the system we have implemented. The patient wears a high-resolution HMD (Kaiser Proview^{TM} XL50) and a pair of data gloves while sitting on the Haptic Workstation^{TM} [12]. The haptic feedback consists on force-feedback on both hands at the level of wrists and fingers. A 22-sensor CyberGlove© is used to acquire the hands gestures used to interact with the virtual objects. A Cyberforce© system applies ground-referenced forces to each of the fingers and wrists.

The virtual environment is controlled by a PC workstation, responsible of maintaining the common semantic model of the environment. The virtual world is edited by the therapist using the handheld device and rendered in higher detail by an OpenGL-based 3D viewer. Collision detection and force-feedback are managed through a proprietary library from Immersion Corporation designed as a control interface for the Haptic Workstation^{TM}.

The handheld device we used is an IPAQ 3970 Pocket PC (XScale at 400Mhz). The interface is programmed in C++, using the eMbedded Visual Tools 3.0 [15]. The graphics rendering on the handheld is done through the DieselEngine library [5]. The choice of DieselEngine was based on the flexibility of its API (similar to DirectX), and its overall performance. The handheld communicates with the PC workstation by means of a wireless network link (TCP/IP).

The semantic model is implemented as a database application programmed in C++ which communicates with the 3D viewer and Pocket PC. It keeps synchronization between the simplified representation of the virtual environment (used on the IPAQ), and the higher resolution of the virtual world that is presented to the patient.

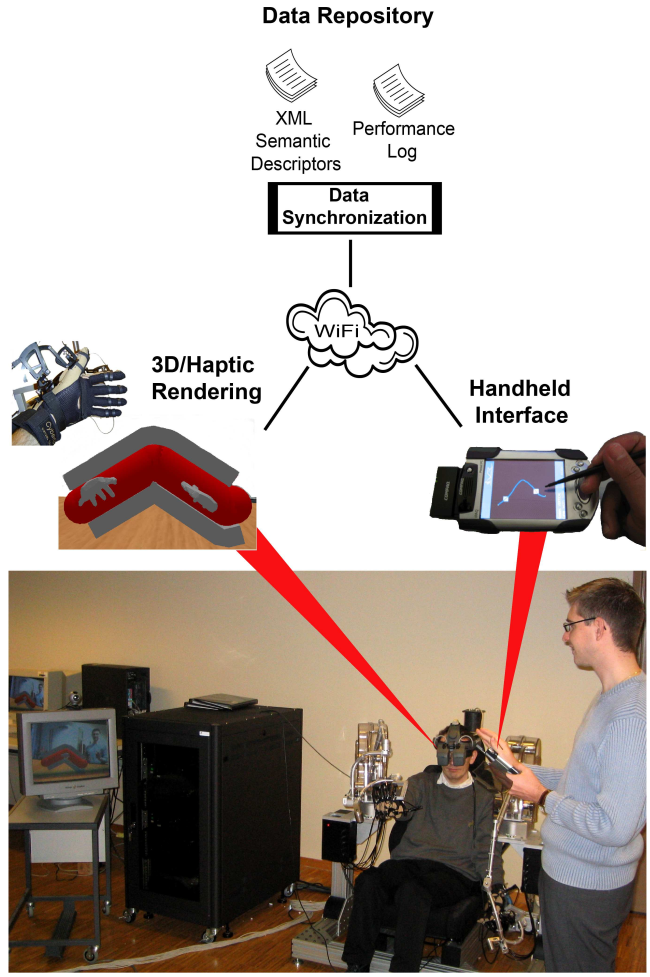

Figure 5: Test application for kinesthetic therapy, the therapist edits the therapy environment and monitors the patient's performance.

6. DISCUSSION AND FURTHER WORK

Preliminary informal tests have been carried on with our first prototype. For the moment, researchers from our lab have played the role of patients and therapists. We observed that the integration of the virtual window is a valuable help to keep the user communicated with the real world. A psychiatrist took a look at our system and found that the "window to the real world" was a very positive improvement compared to other virtual therapy environments. Tests have been realized in which the "therapist" designs an exercise and right after accompanies the "patient" in the execution of the gesture. Thanks to the handheld device, the therapist has a good range of motion freedom and can easily gesticulate with the upper body while monitoring and editing the therapy environment.

The users playing the role of patients were able to follow the gestures of the therapist on the virtual screen. According their comments, the haptic feedback proved to be an efficient way to convey the feeling of interacting with a real object. It was easy to imagine that the 3D pipes were true objects since there was a response when touching them (force-feedback).

Concerning the security of the patients (forces applied are not virtual), the Haptic Workstation disconnects the motors providing force-feedback if the force applied by the user exceeds a certain customizable threshold. The maximum force generated by the system is of 10 Newtons on each arm. Since we can control the amount of force-feedback, there are no risks for a patient with locomotion impairments. On the other hand, force calibration can be an issue. For instance, if the disconnection threshold of the force-feedback is set too low, the haptic effect would disappear. These issues will be studied in detail in future tests.

The architecture we have proposed still requires to take into account the feedback from its target users: real therapists and patients. Comments and suggestions from them will provide us with valuable information to enhance the telerehabilitation system and further refine the concepts we are proposing.

7. ACKNOWLEDGMENTS

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